The Coordination of Transformer Insulation with Line Insulation[1]

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AT the Toronto Convention of the Institute in June 1930, a paper[4] sponsored by the Transformer Subcommittee of the Electrical Machinery Committee was presented to bring before the membership the status of certain work done by the subcommittee in connection with the coordination of transformer and line insulation.

Two things of outstanding importance were included in this paper: first, a recommended practise of expressing the impulse strength of a transformer in terms of the 60-cycle dry flashover of suspension insulators, and second, recommendations for coordinating the impulse strengths of the transformer and the line insulation. These recommendations included either the use of a safety gap of known flashover characteristics connected in parallel with the transformer, or the reduction of the line insulation to a coordinating value for a distance of one-half mile from the transformer, or a combination of either with a suitable lightning arrester. These recommendations referred to standard line voltages of 69 kv. and above.

Since the publication of this paper the principle of coordination has been widely discussed and it appears to have become generally accepted throughout the industry. While practise has shown that the coordination obtained with one-half mile of standardized line insulation has been satisfactory, there has been a gradual change in favor of the use of an air gap for expressing the impulse strength of transformers and for coordinating purposes. Certain advantages possessed by the air gap have contributed to this change. A gap, for example, can be set at any desired level, while a string of insulators affords no chance for close adjustment. The removal of one disk, for instance, from a string of eight, causes a change of approximately 12½ per cent in the impulse flashover value; the difficulties of adjustment are naturally even more pronounced with shorter strings. Furthermore, the air gap localizes the flashover at a point in the system which can be made convenient for maintenance purposes or for the installation of lightning arresters. Where reduced line insulation corresponding to the original recommendations of the Transformer Subcommittee is being used for one-half mile out from the transformer bank, it is, of course, satisfactory for coordination purposes.

The Transformer Subcommittee has recognized the advantages of the air gap and it is the purpose of this brief progress report to bring to the attention of the Institute membership the following revisions which have been made in the previous recommendations:

1. The yard stick used to express the impulse strength of a transformer has been changed from the 60-cycle flashover value of a given line insulator to a coordinating gap with a given length in inches, as outlined in the following paragraphs and the coordinating principle has been extended to include rated circuit voltages as low as 15 kv.

IMPULSE STRENGTH OF TRANSFORMERS

a. Transformers Receiving Standard Tests as Specified in Paragraph 13-400, A.I.E.E. Standards No. 13

Apparatus conforming with the standards should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to earth of a coordinating air gap whose spacing[5] is in accordance with Table I.

TABLE I

Rated circuit voltage	Transformer 60-cycle test voltage	Spacing of air-gap
Kv.	Kv. r.m.s.	Inches
15	31	4.25
23	47	6.25
34.5	69	9.25
46	93	12.25
69	139	18.75
92	185	25.00
115	231	31.50
138	277	38.25
161	323	44.50
196	393	54.50
230	461	64.00

b. Transformers Receiving Other Than Standard Test

For transformers receiving a test different from that given for the rated circuit voltage in *a*, the gap spacing

Continued on p. 974

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[1] Sponsored by the Transformer Subcommittee of the Electrical Machinery Committee, V. M. Montsinger, Chairman, W. H. Cooney, W. M. Dann, H. C. Louis, Basil Lanphier, L. C. Nichols, George Vaughan, F. J. Vogel.

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[4] *Recommendations on Balancing Transformer and Line Insulations*, V. M. Montsinger and W. M. Dann, A.I.E.E. TRANS., Vol. 49, No. 4, 1930, p. 1478.

Presented at the Summer Convention of the A.I.E.E., Cleveland, Ohio, June 20-24, 1932.

[5] Between the ends of two square-cornered, square-cut coaxial rods not more than one-half inch thick up to 69 kv. circuit and not more than three-quarters inch thick for circuits above 69 kv. and so mounted that the rod overhangs its support at least one-half the gap spacing. Also, for circuits above 69 kv. other kinds of air gaps with the recommended spacings such as grading rings on suspension insulators, are satisfactory.

The insulators used as supports should meet the N.E.M.A.-N.E.L.A. 60-cycle flashover requirements for the line voltage.

Normal Frequency Arcover Values of Insulators
as Affected by Size and Humidity

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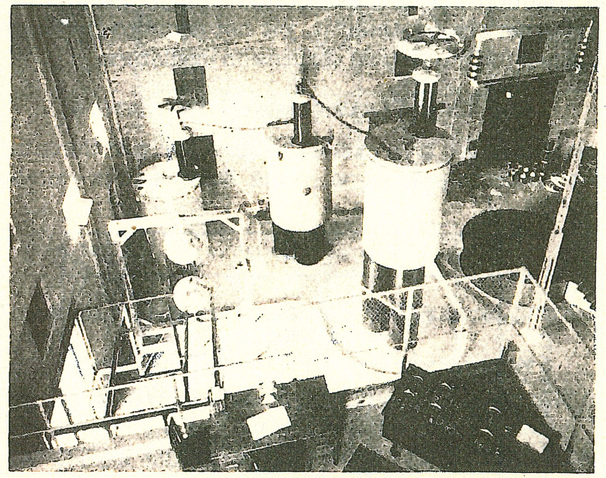
INTRODUCTION

DATA covering the electrical characteristics of comparable insulators as received from different sources are frequently conflicting. A study has been made to establish rules whereby such characteristics can be estimated from the dimensions of the insulators with a reasonable degree of certainty. A long series of tests has been made covering several months with repeated checks upon the same insulator units.

The variation of dry arcovers due to the influence of humidity changes also is considered with approximate correction ratios.

The equipment used for these tests in the High Voltage Laboratory of the Locke Insulator Corporation at Baltimore consists of three transformers in cascade to give 60-cycle voltages up to 1,050,000 r.m.s. Voltages less than 350,000 were obtained by using only one of the three transformers shown in the accompanying illustration. One meter spheres were used as the primary standards for voltmeter calibration for subsequent observations. (A.I.E.E. Standard 4-53 to 57 inclusive.) The laboratory which is fully enclosed, can be kept at any desired humidity and temperature above that of the outside atmosphere. Special equipment is provided for this purpose. Routine tests upon insulators during cold weather were made at standard conditions, 25 deg. cent., (77 deg. fahr.), 65 per cent relative humidity; 0.608 in. mercury water vapor pressure. (A.I.E.E. Standard 410-100,—150). No air density corrections were made. (Standards 41-60 footnote.) Frequent calibrations from the spheres assured that insulators and sphere gaps, which are nearly equally affected by changes in air density, were under the same conditions of test. Thus insulator values were automatically referred to standard air density conditions.



TESTING EQUIPMENT—HIGH-VOLTAGE LABORATORY

Each recorded flashover measurement is the average of at least five successive arcover observations. Considerable variation was frequently noted.

TYPICAL OBSERVATION

Insulator	Pin type 35 kv. rating	Suspension 8–10 x 4¾
Total number observations	8.0	10.0
Minimum voltmeter reading	103.0	255.0
Maximum voltmeter reading	114.0	276.0
Average voltmeter reading	108.0	271.0
Per cent variation	11.0	8.2
Arcover value, kilovolts	111.0	428.0
Approximate transformer ratio	1,000 to 1	500 to 1
Barometer, inches mercury	30.14	30.01
Temperature, dry bulb	78.5 fahr	80.0
Temperature, wet bulb	68 fahr.	68.0
Water vapor pressure	0.572	0.556

SUSPENSION INSULATORS

Tests have been made upon suspension insulators of various spacings and diameters in the vertical position. (A.I.E.E. Standard 41-150, 151.) Insulators tested are:

1. Standard strength cemented 10 in. diameter, 4¾ in., 5⅛ in., 5¾ in. spacing.
2. High strength cemented 10 in. diameter 5¾ in. spacing.
3. Extra high strength cemented 12 in. diameter 7 in. spacing.
4. Hewlett insulators 10½ in. diameter 5½ in. spacing.

The 60-cycle dry and wet flashover values of 10-in. cemented type suspension insulators of all standard spacings are shown on Fig. 1, plotted against actual arcing distance, the shortest air path between electrodes. All dry values regardless of the insulator spacing, fall upon one graph within expected errors of observation. The wet values are affected slightly by design.

The characteristics of the high strength and extra high strength insulators are shown in Fig. 2. The graph for dry measurements is identical with that for the standard insulators, Fig. 1. The wet values again show variations due to design.

The characteristics of Hewlett insulators are shown in Fig. 3. Again the graph for dry values is the same as that of Fig. 1.

Dry arcover values, therefore, for all standard insulators depend solely upon the minimum arc length or tight string distance about the insulators. The wet values are affected by design. In general, insulators with the greatest clear arcing distance between shells show the highest wet values. The remarkable field performance of insulators with fish tail shaped hoods even in dirty locations suggests that insulators should not be judged as much by wet values as by dry. The dry arcover values are measurably affected by the proximity of grounded objects in the neighborhood of the insulator string. This is shown by the double graph at the upper end of the dry curves. The upper graph was obtained with clearances at least twice the length of the insulator string.

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The wet values of Figs. 1, 2, and 3 are plotted as a function of the overall arc length. The most usual design basis is as a function of the wet striking distance or the summation of the air gap distances beneath the insulator assuming the wetted surfaces above are short-circuited out by the water film. A more satisfactory check is so obtained as shown on Fig. 4.

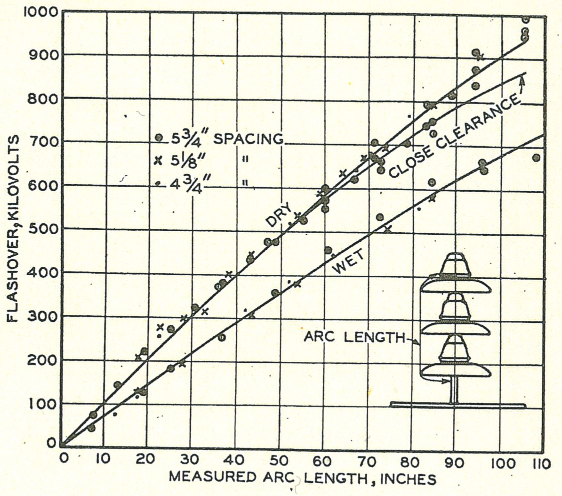

Fig. 1—60-Cycle Flashover Standard Strength Insulators 10 In. Diameter

Errors of individual observations and minor differences due to slight variations in manufacture are removed by obtaining insulator data from the above curves. Expected dry and wet arcover values of various standard and high strength insulators are given on Figs. 5, 6, and 7, plotted as a function of the number of units in the string, calculated from Figs. 1, 2, and 3.

Standard and high strength cemented insulators were tested also in the anchor position at an angle of about 10 degrees from the horizontal. The dry and wet values obtained also are shown upon Figs. 5, 6, and 7 in comparison with the arcover values for the vertical suspension insulators. The dry values are materially lower than for the insulators in the vertical. Wet arcover values are much higher in the horizontal than in the vertical. When the entire surface of the insulator is uniformly wetted a better voltage division between insulator units is obtained with the resultant higher voltage necessary to cause surface breakdown. The wet values in the horizontal are actually equal to, or in some cases with long strings, higher than the dry values in the horizontal.

Most of the tests in the horizontal were made without a jumper loop under the string or a conductor at right angles to it. Insulators in the horizontal position with the conductor at right angles showed dry values materially higher than without it, yet not equal to the values obtained for the vertical suspension insulators.

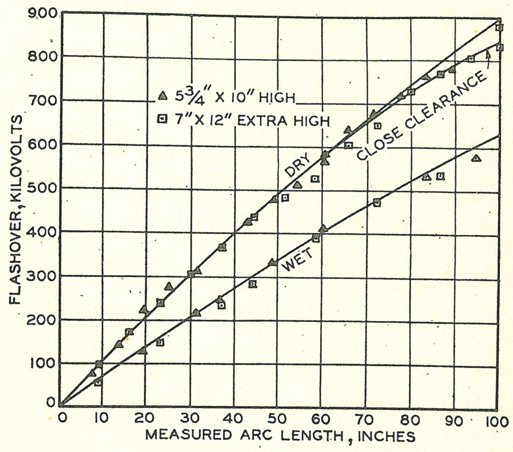

Fig. 2—60-Cycle Flashover High Strength Insulators

Pin Type (Transmission) Insulators

Standard pin type insulators show fairly uniform arcover values in proportion to the distance between electrodes as shown upon Fig. 8. The small contact area of tie wires upon the porcelain causes heavy dielectric flux concentration upon the tie wires with resultant active corona streamer formation at voltages near arcover. Observed data show least uniformity of any of the insulator types because of the erratic action of these streamers. The results of this are shown in the above tabulation of observed data and may be seen later on in the humidity studies. The dry flashover voltage per inch varies from 14 kv. for the small one piece and the smallest multipart insulators. It thence drops at a fairly uniform rate to 11.4 kv. for the largest multipart insulators nominally rated at 70 kv. For the single piece insulators the wet arcover value is uniformly 7 kv. per inch of total striking distance. A higher value is obtained for the standard multipart designs which are quite uniform at 8.9 kv. per inch of total distance. It is most interesting that more consistent comparisons are here obtained on the basis of total striking distance rather than wet striking distance. The low values for the small one piece insulators are due to the large proportion of wetted surface to the total striking distance.

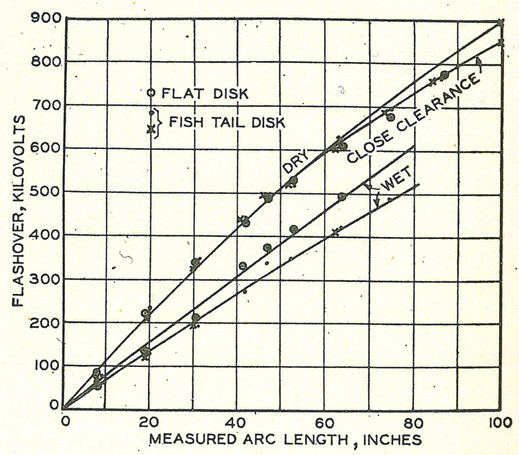

Fig. 3—60-Cycle Flashover Hewlett Suspension Insulators

Outdoor Apparatus Insulators

Outdoor apparatus insulators are pin types modified by adding cemented-on caps for attachments. In comparison with pin types these insulators show less variation between individual observations. The greater contact area of the cap causes less flux concentration and less corona streamer formation at voltages below flashover.

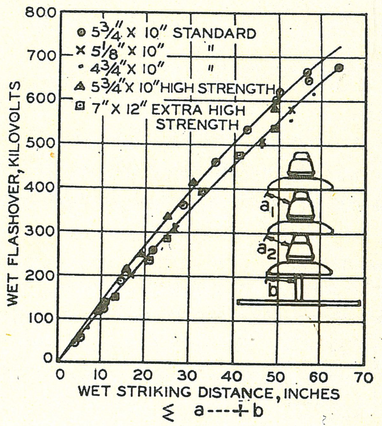

Fig. 4—Wet 60-Cycle Arcover All-Cemented Suspension Insulators

Fig. 9 for dry values covers single and stacked or multiple unit insulators to a height totaling 116 inches dry arcing distance. The lower part of the curve is practically the same as for pin types. The value at 100 inches of height is 7.3 kv. per inch.

The wet values plotted against total arcing distance show considerable variation but less when plotted against the wet striking distance. Both graphs are shown on Fig. 9.

Equipment Bushings, Solid Type

The performance of porcelain equipment bushings (not oil filled) is shown in Fig. 10, for ratings from 7.5 to 69 kv. The field established about the bushing determines the dry values. It is important that the conductor be in place inside the insulator as it will be in service. Much higher values will be obtained without it. The wet values, however, are the breakdown voltages for the water film upon the surfaces. For the larger bushings the wet value is higher than the dry.

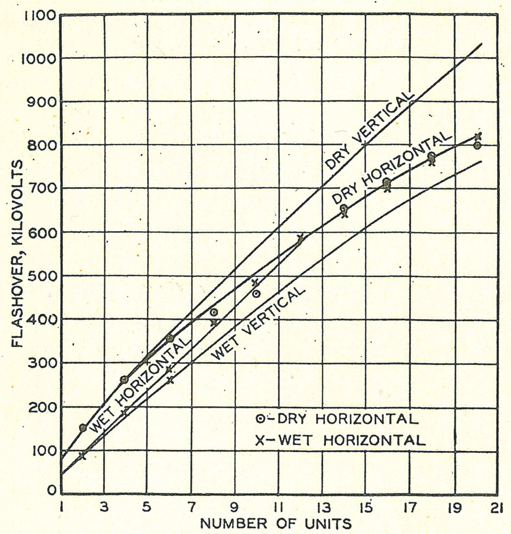

Fig. 5—60-Cycle Flashover Standard Strength Insulators

10 in. diameter, 5¾ in. spacing

Humidity Effects

The effect of humidity upon the dry arcover voltages of insulators may be compared on several different bases:

A comparison of flashover values on the basis of per cent humidity is not satisfactory, for it alone does not account for the total quantity of water in the air.

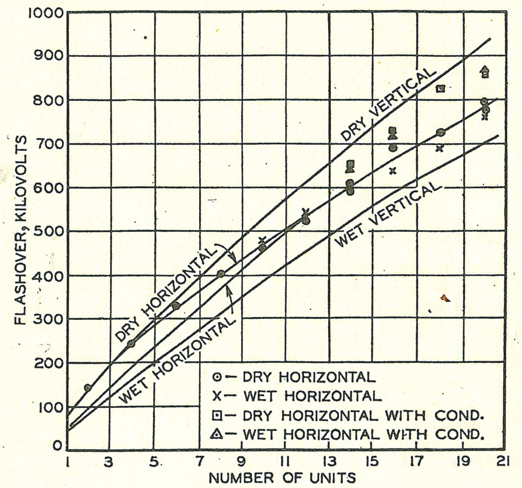

Fig. 6—60-Cycle Flashover Standard Strength Insulators

10 in. diameter, $5^1/_8$ in. spacing

A comparison on the basis of absolute humidity or mass of water per unit of air volume may be satisfactory, but does not account for the molecular activity of the water.

A comparison of flashover may be made on the basis of water vapor pressure in some convenient units such as the barometric method, inches of mercury. This not only accounts for the number of water molecules present, but their velocity as well.

The water vapor pressure as the standard is recommended by A.I.E.E. Standards (41-100). All observations in the Locke Laboratory have been compared upon this basis.

No difficulty has been experienced in maintaining the laboratory at standard temperature (25 deg. cent.—77 deg. fahr.), during the cold months. The laboratory is not equipped to reduce the temperature below that of the outside atmosphere. All tests made during the winter are at the standard temperature and with humidity adjusted as desired. In warm weather tests were made at the outdoor temperature and humidity some-times as high as 95 deg. fahr., and 85 per cent relative humidity.

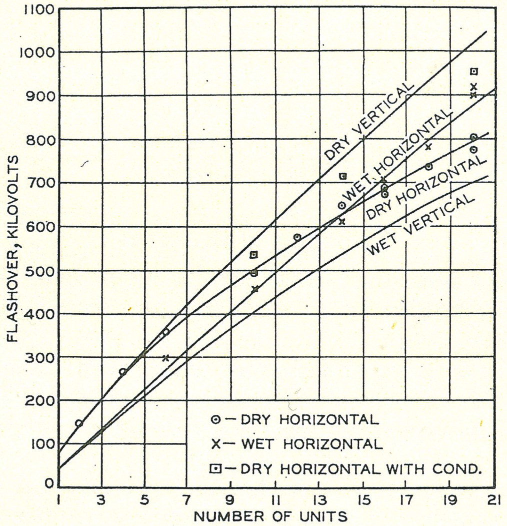

Fig. 7—60-Cycle Flashover High Strength Insulators

10 in. diameter, 5¾ in. spacing

The effect of humidity upon the dry flashover of standard suspension insulators is shown in Fig. 11. Average dry flashover curves have been drawn for strings of various numbers of units. By plotting upon semi-logarithmic paper equal ordinate distances give equal percentage variations. It is thus easy to compare percentage corrections for different strings and percentage variations from the average of individual observations.

The slope of all these average graphs is practically the same. When referred to 100 per cent at the standard water vapor pressure, 0.608 inches mercury the correction at 0.2 inches mercury is − 8 per cent. The correction, therefore, is approximately 2 per cent for each 0.1 inch of mercury variation of water vapor pressure.

The points of observation would be enclosed within an envelope of plus and minus 5 per cent from the curve of averages.

It, therefore, follows that even with the correction for humidity variations a variation of plus or minus 5 per cent in flashover values of suspension insulators must be expected. The insulators used were the same throughout the entire test.

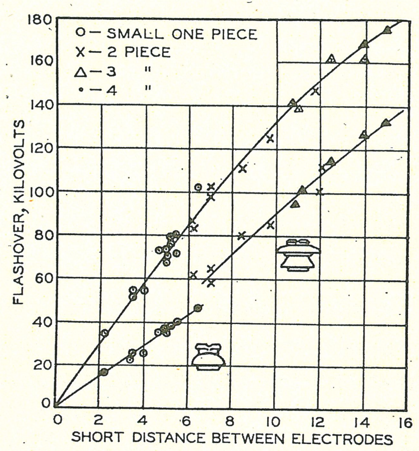

Fig. 8—60-Cycle Flashover Pin Type Insulators

The effect of humidity on flashovers of typical pin type transmission insulators is shown in Fig. 12. But one insulator of each type was tested. Variations shown are not due to manufacturing variations in different insulators. The individual observations fell within an envelope of plus or minus 6 per cent, the broadest of any insulator type tested. The variation in flashover of all insulators between vapor pressures of 0.2 and 0.608 is about 12 per cent. Frequently in testing at standard temperature with relative humidity above 65 per cent, erratic performance and marked fall in flashover was observed. A typical example is shown for the 27 kv. rated insulator. This is believed to be due to the formation of invisible water film upon the surface of the insulator at these higher humidities.

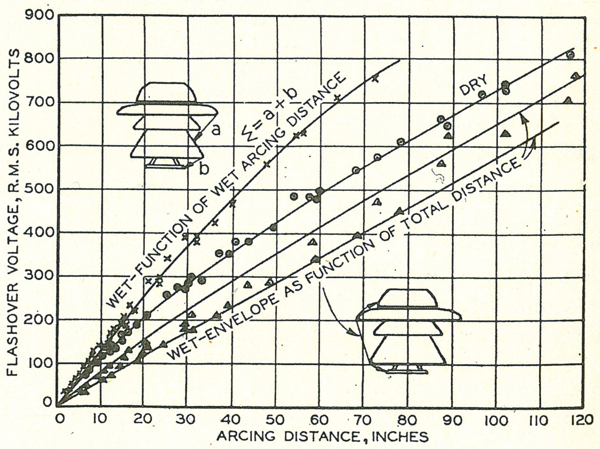

Fig. 9—60-Cycle Flashover Outdoor Apparatus Insulators

Fig. 13 shows the effect of humidity upon typical outdoor apparatus insulators. The points of observations shown upon these graphs in comparison with those for the pin types, Fig. 12, show much more stable performance. This is due to absence of corona streamers as already discussed. The variation from the average curve is not over plus or minus 5 per cent. The correction for the humidity effect is less than for pin types.

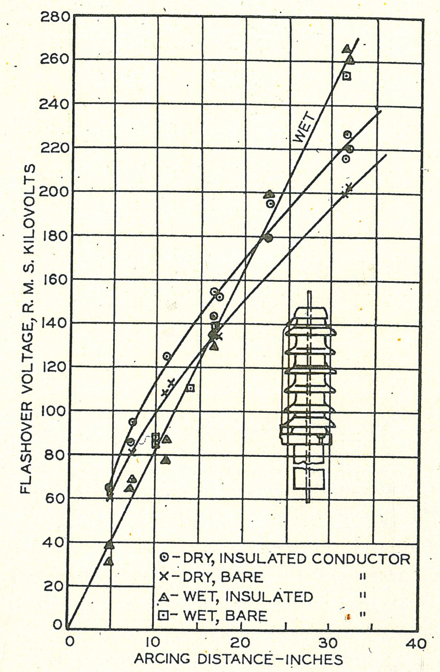

Fig. 10—60-Cycle Flashover Solid Type Equipment Bushings

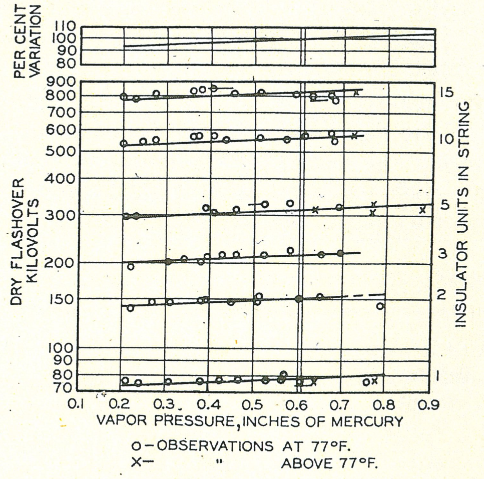

Fig. 11—Effect of Humidity Standard Suspension Insulators

10 in. diameter, 5¾ in. spacing

It is 8 per cent between vapor pressures of 0.2 and 0.608, the same as for suspensions. Points at the upper right hand ends of these graphs are for temperatures well above standard, yet falling closely upon the same graph, indicating that comparison on the basis vapor pressures is quite satisfactory.

A most interesting observation upon an apparatus insulator of the multiple unit type for stacking is shown in Fig. 14. The correction for humidity is the same for this insulator as for the other apparatus and for the suspension insulators, 8 per cent from 0.2 to 0.608 inches mercury water vapor pressure. The variation of observations from the average for the three and six unit stacks falls within an envelope of plus or minus 5 per cent. For a single unit, however, the variation is nearly plus or minus 10 per cent. This checks observations upon other insulators such as the tall apparatus and the suspension insulators, indicating that for great lengths the percentage variations are somewhat less and the performance of the insulators more stable.

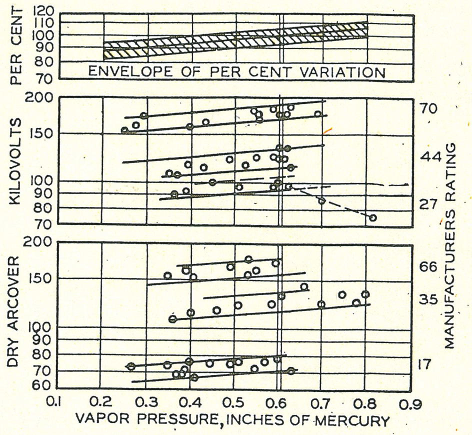

Fig. 12—Effect of Humidity on Flashover Pin Type Insulators

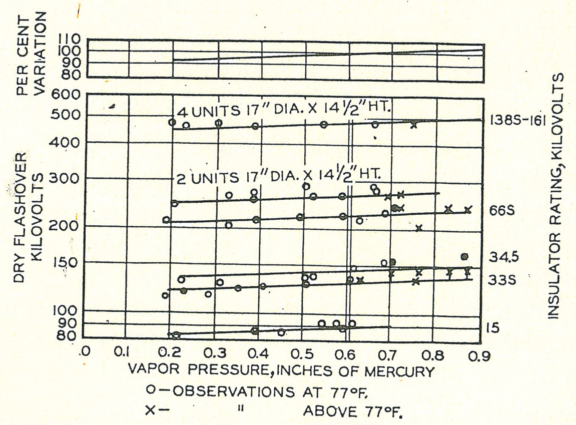

Fig. 13—Effect of Humidity on Typical Apparatus Insulators

The performance of porcelain equipment bushings with varying humidity is shown in Fig. 15. The correction for humidity with these bushings is the same as for all others except the pin types.

A tabulation has been made, summarizing the above data as follows:

TABLE I

Insulator type	Dry value Arc length Kilovolts / Inch	Wet value Arc length Kilovolts / Inch	Wet value Wet striking distance Kilovolts / Inch	Humidity correction per 0.1 in. mercury water vapor pressure
Suspension:				
0 to 100 in.				
Standard cemented	10.5 to 9	7 to 6.8		2 per cent
High strength cemented	10.5 to 9	7 to 6.3	14 to 10.6	
Hewlett flat disk	10.5 to 9	7.5		
Hewlett fish tail	10.5 to 9	6.5		
Pin types				
Small	14	7.0		3 "
Multipart	14 to 11.4	8.9	(Erratic)	3 "
Apparatus insulators 0 to 110 in. dry arcing distance	11 to 7.3	8 to 5.7 (Erratic)	13 to 10.4	2 "
Equipment bushings				
Solid type	13.6 to 6.75	8.3		2 "
(With bare conductor)	12.4 to 6.1	8.3		

Where two figures are given above first applies to small insulators, second to the largest with fairly uniform steps in between, except as noted as erratic.

Effect of Surface Conditions

In an effort to determine how the above rules for insulator flashover might be affected by surface conditions, representative insulators were exposed above the smoke boxes of a battery of beehive kilns for a period of several months. The surfaces of these insulators at the expiration of this period were thoroughly covered with a dirt deposit consisting largely of carbonaceous material mixed with a certain amount of clay dust and ordinary floor dirt. The coating was rather hard, due to the baking action of the heat from the kilns.

Other insulators of exactly the same type were thoroughly coated with a salt crust by spraying with a concentrated salt solution and allowing to dry.

The insulators were then flashed over, first clean and dry, then salt coated and dry, and finally dirt coated and dry. Tests were repeated with the insulators in a steam chamber filled with steam at approximately 100 deg. temperature to simulate fog conditions. Finally some of the insulators were tested under A.I.E.E. Standard Wet Flashover Test. The results of the tests are shown in the following tabulation.

It will be noted that there is very little reduction in the dry flashover of the insulators when dirty. Dry tests on the salt coated insulators were made at two humidity conditions. The first group of tests yielding the higher values in the tabulation were made at approximately 77 deg. dry bulb temperature, 65 per cent relative humidity. The second group of tests made at approximately 77 deg. dry bulb temperature and 79 per cent relative humidity gave flashover values materially lower, probably due to the absorption of water by the salt, at this relative high humidity. At the lower humidity the dry flashover of the salted insulators is nearly the same as that of clean insulators.

When subjected to artificial fog the salt coated insulators showed in most cases very marked decline in flashover. The flashover of the dirt coated insulators was also decreased but not so severely.

In a further effort to study the effect of surface conditions on the flashover of insulators, other insulators were hung on the roof of the laboratory for a period of one year, each insulator being flashed over approximately once a month. Since the laboratory is in a heavy industrial district the insulators were subjected to soft coal smoke and industrial gas fumes. The results of the tests over a period of one year are tabulated. All flashover measurements were made at a time when the insulators were apparently thoroughly dry.

TABLE II

Nominal rating or number of units	Type of insulator	Dry				In A.I.E.E. standard wet flashover test			In steam fog		
			Salt coated								
		Clean	79% humid.	65% humid.	Dirty	Clean	Salt coated	Dirty	Clean	Salt coated	Dirty
20 kv	Pin type A	67	41	72					22.5	23	
20 kv	Pin type B	69	62	77					30	20–26	
35 kv	Pin type	120	97	112	116		34–63		56	24	48
44 kv	Pin type	135	97	114	128	95	52–80	67–74	74.5	34	68
55 kv	Pin type	137	90	140	136				78–89	48	85
66 kv	Pin type	161		164.5					132	51	
70 kv	Pin type	178	185	189	178				132	55	83
1 unit	5¾ x 10 in. disk	77	34	75	69	48	27–44	36–53	33	23	32.5
3 units	5¾ x 10 in. disk	204			205				139		114
9 units	5¾ x 10 in. disk	535		479							
9 units	5⅛ x 10 in. disk	485		454							

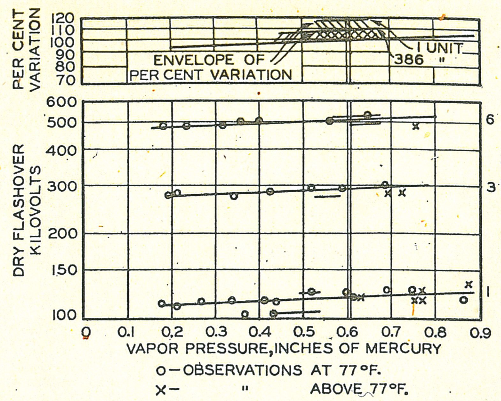

Fig. 14—Effect of Humidity on Apparatus Insulator Multiple Unit Type

10 in. diameter, 9¾ in. high

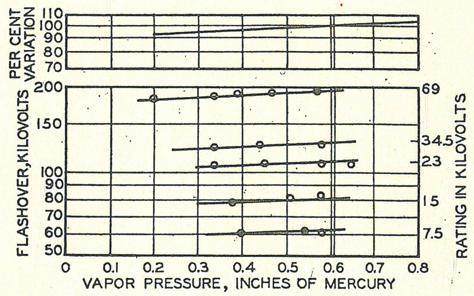

Fig. 15—Effect of Humidity on Porcelain Equipment Bushings

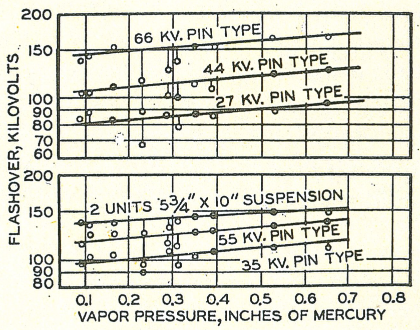

Fig. 16—Flashover of Dirty Insulators as a Function of Humidity

These tests were, of course, made at such humidity and temperature as happened to be existing at the time. The points have been plotted on Fig. 16. It will be noted that the curves are identical with those of Figs. 11 and 12. There are certain points on each of the curves which fall materially below the average. It is believed that in these cases the dirt film on the surface was very slightly moistened. Since most of the tests were made in the morning it is quite possible that in these cases there was still a certain amount of invisible dew remaining on the surface of the insulators.

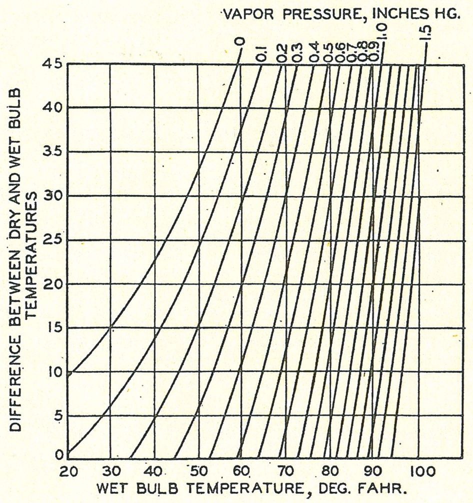

Fig. 17—Psychrometric Chart

From Smithsonian Meteorological Tables. Barometer = 30.00 in. Hg.

Conclusions

The relations found between arcing distance and insulator flashover and between humidity and insulator flashover are indicated in the foregoing curves and tabulations. At very high relative humidities there is in some cases a scattering of test results with points falling below the humidity curves. This is believed to be due

TABLE III

Time of exposure	0	1 Month	2 Months	3 Months	4 Months	5 Months	6 Months	7 Months	8 Months	12 Months
Dry bulb temp.	82	65	50	43	27	30	44	52	61	74
Wet bulb temp.	68	56	48	41	24	27	38	48	56	69
Vapor pressure	0.533	0.352	0.314	0.235	0.092	0.111	0.163	0.292	0.396	0.659
Barometer	30.04	30.15	30.25	29.91	30.09	29.94	29.57	30.06	30.00	29.96
Rating and type of insulator										
27 kv. pin type	89	86.5	78	68	83.5	88	82.5	86.5	85.5	95
35 kv. pin type	109	101.5	94.5	89.5	96.5	104.5	102.5	108	106	109
44 kv. pin type	123	111	100	88	103	105.5	110	101	108.5	127
55 kv. pin type	132	125	111	95	112	122	124.5	113	129	136
66 kv. pin type	164	152	135	116	136	141	152	126.5	151	164
2 units 5¾ in. x 10 in. suspension type	148	142	135	122	136	132	134	129.5	143	144

to the precipitation of a fine moisture film on the surface of the insulators.

Throughout the common range of temperatures (20 to 100 deg. fahr.) the relation between vapor pressure (expressed in manometric inches of mercury) and absolute humidity (expressed in grains per cu. ft.) is such as to make no practical difference which of them is used as the basis of measurement.

The same humidity corrections are applicable to dry dirty insulators as to clean insulators.

Dry dirt only slightly lowers the flashover of insulators. A small amount of moisture greatly reduces the flashover of dirty insulators, particularly if the dirt is of a saline nature.

At high relative humidities the flashover of salt coated insulators is materially reduced due to absorption of water by the salt.

Insulators can be checked for flashover from data given in Table I which also gives humidity correction factors. Deviation of individual flashover voltages from the average are not fully explained by humidity variations alone. After correction for humidity has been made a variation of about plus or minus 5 per cent remains in some cases.

NOTE: Vapor pressures may be obtained from barometric and dry and wet bulb thermometer readings with the assistance of the Smithsonian Meteorological Tables from which Fig. 17 has been drawn.

From this vapor pressures may be obtained with sufficient accuracy for the purpose.

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3. Low-voltage lightning arresters shunted across the regulator series windings operate in series with the bus arresters and limit the rise of voltage on the line side of the regulator to the sum of the breakdown voltages of these two sets of arresters.

4. Lightning arresters at the substation end of the cable limit the voltage on the pothead and the regulator; and, acting in combination with the cable pole and the bus arresters, they will limit the voltage in the cable to the drops across the arresters.

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should correspond to the test which the transformer will receive, in accordance with the relation between test and gap spacing given in *a*.

2. The *Recommendations for Coordinating Transformer Insulation with Line Insulation in the Field*, included in Part II of the Montsinger-Dann paper of June 1930, will be eliminated from the recommendations of the subcommittee. These recommendations involve the three methods of coordinating transformers with line insulation referred to in the opening paragraphs of this report. The coordinating gap referred to in (1) replaces the eliminated recommendations and serves the following purposes:

It establishes the standard of impulse strength required in the design of a transformer.

In practise it limits the magnitude of incoming surge voltages to values less than the impulse strength of the transformer, thereby establishing coordination.

A lightning arrester may be used in conjunction with the coordinating gap to prevent system outages.

Characteristics of Surge Generators for Transformer Testing

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Synopsis.—*The requirements and limitations of surge generators for transformer testing can be summed up as follows:*

The voltage that can be obtained is, in the first place, largely determined by the capacity of the surge generator when the capacity of the transformer is great.

If a wave is desired without superimposed oscillations, it is necessary to insert resistance within the generator. The front of the surge then depends upon the inductance of the generator and the capacity of the transformer. This is a matter inherent to all surge generator test circuits. Thus, in general, waves of very steep front cannot be obtained with large transformers.

Further, the inserted resistance also limits the voltage by an amount dependent on the proportion of this resistance to the load resistance.

For transformers of low inductance, the length of the wave obtained is largely determined by the capacity of the surge generator. This results in a requirement of large generator capacity if very long waves are to be produced.

If the lead between the transformer and generator is appreciably long, other oscillations will be set up which are highly damped but are appreciable at the generator end. These oscillations occur on the front of the wave only, and will be prominent when measurements are taken at the surge generator.

INTRODUCTION

It is the purpose of this paper to consider the characteristics of surge generators in relation to their application to the surge testing of electrical apparatus, particularly transformers. Previously, surge testing has been mostly confined to gaps, insulators, bushings and similar insulation structures. Since the surge testing of transformers has been shown to be desirable,[1] the characteristics of surge generators in testing transformers become of great interest, particularly in the formulation of standards or rules for such testing.

CIRCUITS OF SURGE GENERATOR AND TESTED APPARATUS

The surge generator consists of a bank of condensers or a bank of groups of condensers, each condenser or group charged in parallel to a given potential and all condensers or groups discharged in series through gaps into an external resistance or series of resistors.[2] In the circuit diagram of Fig. 1a, these primary circuit elements are simply represented as a lumped surge generator capacity C_s, charged at potential E, and suddenly discharged through the gap or gaps G into the load or discharge resistance R. An inductance L_s is inevitably entailed in the condenser bank circuit and in leads connecting to the load resistance, also in leads connecting to tested apparatus. Likewise, a resistance R_s is present in the condenser bank circuit, connecting leads, etc., and, for reasons explained below, this resistance is purposely increased and adjusted to have a given proper value. Furthermore, the condenser bank structure and the accessory apparatus of the generator (spheres, leads, insulator strings, etc.) all have capacity to ground. This leakage capacity to ground may, for engineering purposes, be considered as a lumped capacity C_2. Thus, the circuit diagram of Fig. 1b represents in simplified form the equivalent circuit of the surge generator proper.

Apparatus tested, such as bushings, insulators, gaps, etc., are in effect lumped capacity loads. In case the apparatus connects to the generator through a short lead, the diagram of Fig. 1b also represents the equivalent circuit of the generator with load. The capacity C_T is the load capacity; C_L represents the leakage capacity to ground of the generator combined with the load capacity.

Transformers and similar inductive apparatus introduce other elements in the test circuit of the surge generator, with resultant modifications in the surge generated. In the case of transformers with substantially uniform voltage distribution, the equivalent circuit of the transformer consists in effect of a capacity C_T shunted by an inductance L_T. The total load capacity due both to the surge generator and the transformer may be considered lumped in a capacity C_L, as shown in the circuit diagram of Fig. 2. Surge testing is also applied to transformers in which the voltage distribution departs from uniform.[1] The equivalent circuit of these transformers may be represented in simplified

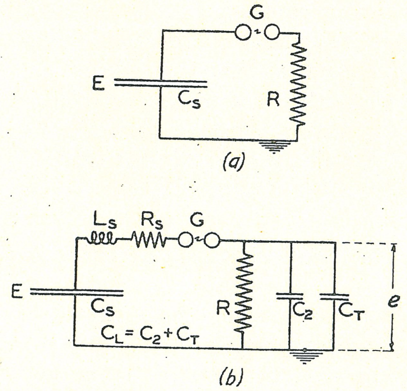

FIG. 1—CIRCUIT DIAGRAM OF SURGE GENERATOR WITHOUT LOAD AND WITH CAPACITY LOAD

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[1] For references see Bibliography.

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